Int J Life Cycle Assess (2012) 17:593–603
DOI 10.1007/s11367-012-0394-y

SUSTAINABLE DEVELOPMENT

A PCA-based method for construction of composite sustainability indicators

Tao Li · Hongchao Zhang · Chris Yuan · Zhichao Liu · Chengcheng Fan

Received: 6 August 2011 / Accepted: 17 February 2012 / Published online: 7 March 2012

Abstract
Purpose Sustainable manufacturing is practiced globally as a comprehensive strategy for improving the sustainability performance of the manufacturing industry. While sustainability is characterized into such three dimensions as economic, environmental, and social, currently, there is no quantitative method yet to measure the so-called "sustainability" in the manufacturing industry. The objective of this research is to develop a comprehensive and effective quantitative method to measure the overall sustainability performance of manufacturing companies.
Methods In this paper, an integrated methodology is presented for the development of composite sustainability indicators based on principal component analysis (PCA). In developing this integrated approach, both industry and academia surveys are conducted to identify what sustainability indicators are favored by the sustainable manufacturing community. A unique index is then generated to measure the overall sustainability performance of industrial practices. The methodology can be used for benchmarking the overall sustainability performance of various manufacturing companies.
Results A case study is conducted on a total of 11 global electronic manufacturing companies. The overall sustainability performance of these companies are measured, benchmarked, and ranked. The results showed that PCA is an effective approach for constructing composite sustainability indicators across environmental, economic, and social dimensions.
Conclusions From this research, it is found that industry and academia have different views on the sustainability measurement, evidenced by different weights put on the same indicator in industry and academia. The case study demonstrated that the methodology presented in this paper is an effective tool for comprehensive measurement of sustainability performance of manufacturing companies. Strengths and weaknesses of each company can be identified. Then, the recommended improvements can be suggested based on the study of each of the individual indicators.

Keywords Corporate sustainability · Industry and academia surveys · Life cycle assessment · Sustainable development · Sustainability indicator

Responsible editor: Andreas Jørgensen

T. Li (✉) · H. Zhang · Z. Liu
School of Mechanical Engineering,
Dalian University of Technology,
No. 2 Linggong Road, Ganjingzi District,
Dalian, Liaoning 116023, People's Republic of China
e-mail: litao@dlut.edu.cn

H. Zhang
Department of Industrial Engineering, Texas Tech University,
Lubbock, TX, USA

C. Yuan
Department of Mechanical Engineering, University of Wisconsin,
Milwaukee, WI, USA

C. Fan
Department of Management Science and Engineering,
Stanford University,
Stanford, CA, USA

1 Introduction

The manufacturing industry faces many challenges in today's competitive global market. Sustainable development of the manufacturing industry is promoted globally as a result of the official responses to both the Brundlant Commission (WCED 1987) and the United Nations Conference on Environment and Development (Quarrie 1992). Many counties have adopted sustainable manufacturing as a national strategy to promote

and support the continuous growth and expansion of the manufacturing industry.

Economic performance is no longer the only factor for measuring the success of an industrial company. The measurement has been extended to environmental impacts and social benefits of a company including such factors as industrial emissions into the environment, materials and energy use, employees' satisfaction rate, employee training and compensations, etc. The economic, environmental, and social measures together consist of an integrated measure for the sustainability performance. When it comes to real manufacturing industry, this resulted in the generation of the "corporate sustainability" concept, as a need for measuring the overall sustainability performance of a company.

Corporate sustainability, sometimes also known as corporate citizenship, or corporate stewardship, is a measure of a company's performance in conducting a responsible and ethical business. For corporate sustainability, companies are expected to assume all their responsibilities resulting from the impact of their business activities on the economy, environment, and society. The devolvement of corporate sustainability relates closely to sustainable development (Aras and Crowther 2007), since this is important for long-term success and growth of a company's business. In the practice, corporate sustainability has different meanings and interpretations, since different companies have different businesses and strategies. In the past, Dahlsrud (2008) listed and analyzed 37 definitions of corporate sustainability which showed that the existing definitions are more towards a larger degree of congruency. Generally, the dimensions of corporate sustainability are five, namely environmental, social, economic, voluntariness, and stakeholder. The dimensions of existing corporate sustainability definitions range from one to five. This paper takes such three dimensions as environment, social, and economic perspectives, through the development of a quantitative index to construct composite sustainability indicators (CSI).

Over the last 20 years, environmental sustainability has been intensively studied, and the tools that effectively evaluate environmental concerns, such as life cycle assessment (LCA) and carbon footprinting, have been developed. LCA considers the entire life cycle of a product or processes providing a comprehensive view of the environmental aspects and a more accurate picture of the truth of environmental trade-offs in product and process selection (SAIC 2006). While LCA is sufficient to conduct comprehensive environmental performance analysis, what remains as a challenge in current sustainability analysis of manufacturing is the need for improved understanding of how manufacturing processes affect the economic and social dimensions of sustainability (Hauschild et al. 2008).

The research of this paper consists of two objectives. The first research objective is to find out current sustainability measurement practices adopted by companies and identify what sustainability indicators those companies are currently using. While the number of sustainability indicators in the literature is growing, only a few of them are applicable towards the understanding of corporate sustainability (Veleva et al. 2001). Therefore, it is important to know the current status of sustainability measurement in today's industrial practices. The second research objective is to develop a unique single index to measure the composite sustainability with environmental, economic, and social dimensions (Parris and Kates 2003). Indicators selected to measure the sustainability should be integrated into a scientific index that contains the three dimensions of sustainability and, at the same time, is easy to be understood by the end users (Soler and Soler 2008).

This paper investigates the use of a statistical multivariate methodology, principal components analysis (PCA), in the construction of composite sustainability indicators for corporate sustainability performance measurement of the manufacturing industry. PCA is a mathematical method, developed by Karl Pearson in 1901, for transforming the observations from possibly correlated variables into independent variables which are called principal components (PCs) using orthogonal transformation (Pearson 1901). Now PCA is popularly used as a tool in exploratory data analysis and for making predictive models. For example, Jollands et al. (2004) uses PCA to provide fertile ground for an inquiry into developing an aggregate measure of eco-efficiency. Soler and Soler (2008) adopt PCA to assess the sustainability of the apple trade in Spain.

Based on the PCA method, we constructed a unique CSI that provides reference for the difficulties in conducting economic and social LCA, such as how to choose and quantify economic and social indicators and distribute their weight. Secondly, while traditional LCA mainly focuses on products and processes, the CSI cover the entire activities of industrial practices. Thirdly, the results of traditional LCA are multiple parameters for environmental assessment; the presented CSI in this paper can convert the impacts into a single score to measure and assess all sustainability of an industrial company.

2 Sustainability indicators

2.1 The chosen criteria of corporate sustainability

The first step in conducting the survey is to select a set of indicators to be used. Global Reporting Initiative is served as a good source of references for the selection. Besides, some indicators also can be chosen from related publications (Krajnc and Glavic 2003; Veleva and Ellenbecker 2001). The criteria of indicator selection should "generally include policy relevance, analytical soundness and measurability, so that the indicators can translate and deliver the concise, scientific and credible information in a manner that can be readily understood and communicated for decision-makers and other target audiences"

(OECD 2002). Besides, some other criteria such as spatial representation, transparency, ease of interpretation, and potential inclusion in integrated assessment tools were also suggested to be considered (Erhard et al. 2002). In this research, the following three criteria have been chosen in measuring corporate sustainability (Wei et al. 2007):

Criteria 1: Policy relevance and representativeness
Criteria 2: Analytical soundness
Criteria 3: Readily available and reliable data

In order to identify what sustainability indicators companies really adopt in practice, industry and academia surveys are conducted. Table 1 shows the indicators used in our surveys in both industry and academia. All these indicators are categories into the three dimensions of sustainability, i.e., environmental indicators, social indicators, and economic indicators.

2.2 Industry survey results

Ten respondents from eight industrial companies (including companies and their subsidiaries) participated in this survey. These companies are all large or medium sized in such industrial sectors as electronic products, automobiles, semiconductors, valves, and fluid-handling components. These companies have forged close and friendly cooperative relations with the universities and are willing to join the research. Figure 1 illustrates the results from the industry surveys, where usage percents and weights are calculated as the average results from the respondents.

Figure 1 shows a scatter plot of the distribution of all indicators in a two-dimensional space. The x axis is the averaged weight of importance with scores between 1 and 5. Since the survey scores are all between 2.5 and 4.5, so the x axis range is selected in this range. The y axis is the percentage of current usage, ranging from 0 to 1 (100%). With two reference lines added to the plot area using the middle point of each axis, the x axis is 3 and the y axis is 0.5, and the scatter plot is divided into four areas—not in use and not important, in use but not important, not in use but important, and in use and important.

2.3 Academia survey results

Using the chosen indicators of the survey in Table 1, we conducted academia surveys. Respondents from seven different research institutions and universities participated in the academia survey. All of them are researchers in the sustainability field. A professional AHP software—ExpertChoice—was used in this research to analyze the inputs and calculate the relative weight of importance on each indicator from the pairwise comparisons. From the academic survey, seven sets of weights were derived after the calculation. The average weights for economic and social indicators are shown in Table 2.

From the surveys' results, we found that industry and academia have different views on the same indicators. For example, EP1 (percent of suppliers without environmental health and safety (EHS) violations) received the highest weight of importance from industry surveys, but got the lowest weight from academia.

3 Construction of composite sustainability index

3.1 A brief description of PCA

The central idea of PCA is to reduce the dimensionality of a data set consisting of a large number of interrelated variables, while retaining as much as possible the variation present in the data set. This is achieved by transforming to a new set of variables, the PCs, which are uncorrelated and which are ordered so that the first *few* retain most of the variation present in *all* of the original variables (Jolliffe 2003). PCA can be done by eigenvalue decomposition or singular value decomposition of a data covariance matrix, usually after standardizing the attribute data. The results of a PCA are usually discussed in terms of component scores (the transformed variable values corresponding to a particular case in the data) and loadings (the weight by which each standardized original variable should be multiplied to get the component score) (Shaw 2003).

There are some critical conditions for conducting PCA. First of all, what sustainability indicators are really preferred by companies? A set of indicators should be chosen to characterize the sustainability of the environmental, economic, and social dimensions. We have conducted industry and academia investigations to determine the indicators which are needed to be assessed. Secondly, the environmental, economic, and social sustainability indicators should be constructed separately using PCA and then combined together to form a composite sustainability index for overall sustainability performance analysis. Lastly, the available and reliable data are indispensable. We collected the data of indicators from real-world electronics manufacturing companies in the case study. Details are elaborated below.

3.2 Essentials of constructing the index

It often seems easier for the general public to interpret composite indicators than to identify common trends across many separate indicators, and they have also been proven useful in benchmarking country performance (Saltelli 2007). However, composite indicators can also deliver misleading policy messages if they are poorly constructed or misinterpreted. The results could invite users (especially policy makers) to draw simplistic analysis or politic conclusions. The composite

Table 1 The indicators of the survey

Environmental indicators	Energy and material usage (EM)		
	EM1	Material usage
	EM2	Percent of materials used that are recycled input materials
	EM3	Energy consumption
	EM4	Percent of renewable energy
	EM5	Energy saved due to conservation and efficiency improvements
	EM6	Total water consumption
	EM7	Percent of recycled/reused water
	Emissions to natural environment (NE)	
	NE1	Total greenhouse gas emissions by weight
	NE2	NO_x, SO_x, and other air emissions by weight
	NE3	Total water discharge volume
	NE4	Total solid waste weight
	NE5	Weight of hazardous waste
Social indicators	Workers (W)	
	W1	Lost work days due to illness or injury
	W2	Average hours of employee training per year
	W3	Employee job satisfaction rate
	W4	Employee turnover rate
	W5	Gender ratio
	Community development and social justice (CS)	
	CS1	Community spending and charitable contributions
	CS2	Number of community–company partnerships
	CS3	Percent of products consumed locally
	CS4	Ratio of company wage compared to local minimum wage
	CS5	Percent of investment in human rights clauses
Economic indicators	Economic performance (EP)	
	EP1	Percent of suppliers without EHS violations
	EP2	Investments in environmental protection
	EP3	Investments in local suppliers
	EP4	Costs associated with EHS compliance
	EP5	Organization's openness to stakeholder review and participation
	Products (P)	
	P1	Percent of products designed for disassembly, reuse, or recycling
	P2	Percent of products with an environmental label
	P3	Percent of products with take-back policies in place
	P4	Customer satisfaction
	P5	General guidelines for warning and safety labels

indicator should ideally measure multidimensional concepts which cannot be captured by a single indicator, e.g., competitiveness, industrialization, sustainability, single market integration, knowledge-based society, etc. In fact, composite indicators must be seen as means of initiating discussion and stimulating public interest (Laurent et al. 2010). Their relevance should be gauged with respect to constituencies affected by the composite index.

PCA is a variable reduction technique that can be used when variables are highly correlated; it reduces the number

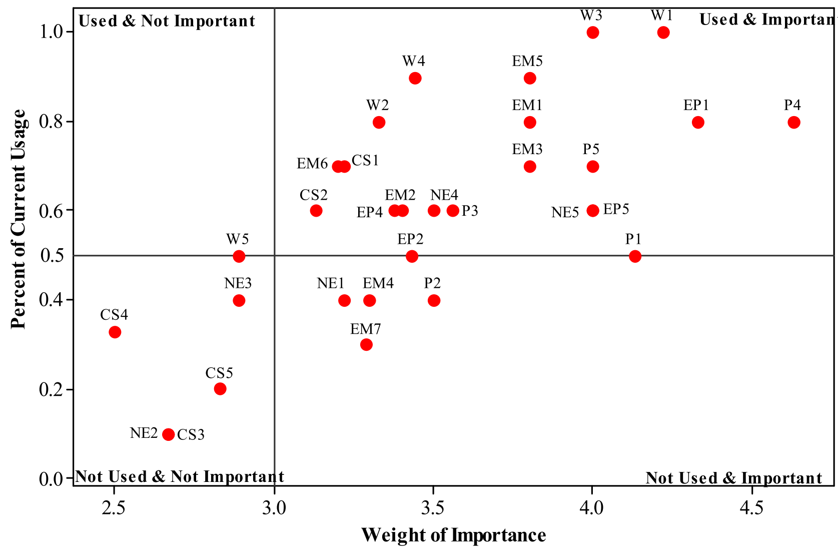


Fig. 1 Industry survey results

of observed variables to a smaller number of principal components that account for most of the variation in observed variables (Hossein and Shinji 2011). These characteristics are the reasons why PCA fits to construct the composite sustainability index.

3.3 Construction of the index

A composite environmental indicator was constructed using PCA with a matrix of p indicators × n company/year. The selection of p indicators can be defined according to the actual industry surveys or the standards established. In the application of the PCA method, all the values need to be signed as positive or negative in order to make them unidirectional (Jha and Murthy 2003). The data are then normalized to zero mean and unit variance, to calculate eigenvalues and the amount of variance explained by each PC. The number of components retained in the analysis is determined by the accumulative

Table 2 Academia survey results

EP	Weight	P	Weight
EP1	0.137	P1	0.231
EP2	0.220	P2	0.140
EP3	0.199	P3	0.203
EP4	0.201	P4	0.278
EP5	0.244	P5	0.148
W	Weight	CS	Weight
W1	0.248	CS1	0.174
W2	0.167	CS2	0.160
W3	0.168	CS3	0.150
W4	0.179	CS4	0.327
W5	0.239	CS5	0.188

amount of variance that can reach up to 90%. Then, the value of the eigenvectors and loadings of variables with PCs can be computed. The loading of the PCs can be calculated through:

$$l_{kj} = \sqrt{\lambda_k} e_{kj} \tag{1}$$

where, l_{kj} is the loading of the PCs, λ_k is the eigenvalue of the component k, and e_{ij} is the eigenvector.

Then a single environmental sustainability index can be calculated as:

$$\mathrm{PCA_{Env}}(i) = \frac{\sum_{k=1}^{j} F_{ki}\sqrt{\lambda_k}}{\sum_{k=1}^{j}\sqrt{\lambda_k}}, i = 1, 2\cdots n \tag{2}$$

where F_{ki} is the coordinate of the company i in the component k (and j components are retained, $j \le p$), and λ_k is the eigenvalue of the component k. In Eq. (2), $\sqrt{\lambda_k}$ is used as weighting factors to calculate the final synthesized coordinate of each company. This index can give information about the relative value of environmental sustainability between the studied companies. The higher the index is, the better the environmental sustainability of the companies.

A composite economic and social index is also constructed by PCA using a matrix of q indicators × n company/year. PCA is performed in a similar way as described above, and the aggregation of data into a single economic and social sustainability index ($\mathrm{PCA_{E\&S}}$) is computed in a similar way as Eq. (1).

A composite sustainability index is then built up considering environmental, economic, and social indicators developed above. PCA is used on a matrix of r indicators × n company/year. Aggregation is done as shown in Eq. (1), and a $\mathrm{PCA_{Stn}}$ index is then computed.

p, q, and r are the numbers of the indicators separately selected to measure environment, economic, and social, and composite sustainability. In this method, $p+q \geq r$, it means the indicators for composite sustainability need to be selected from the environment, economic, and social indicators. But the indicators of composite sustainability can sometimes become lesser than the sum of the numbers of the indicators of environment, economic and social.

4 Case study and results analysis

In this study, a case study is conducted to illustrate the real applications of the developed method in the industrial setting. A total of 11 worldwide electronic manufacturing companies are investigated to demonstrate the methodology. In order to keep the confidentiality of the industrial data, all real-world electronic manufacturing companies are represented by company 1 to 11 and used for an anonymous analysis. For the composite sustainability index development, a total of 12 indicators are selected as follows:

1. Environmental indicators: greenhouse gas emissions, total energy consumption, total waste weight, water consumption, waste recycle rate, hazardous waste weight
2. Economic indicators: net income, R&D expenditure
3. Social indicators: work-related employee injury rate, charitable contributions, female percentage, female percentage in management levels

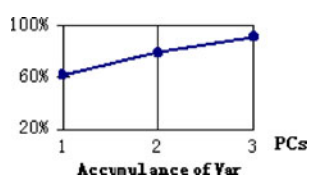
First, PCA is used to analyze the six environmental indicators using MiniTab software. Table 3 shows the analyzed results including correlation matrix, eigenvalues, eigenvectors, accumulation of variance, and the loadings of correlated indicators.

Three principal components were retained, and they explained 91% of the total variance of the data. The first

Table 3 PCA results of environmental indicators

Environmental indicators						
Correlation matrix	1.000	0.399	0.450	0.264	0.035	0.107
	0.399	1.000	0.279	0.684	−0.085	0.060
	0.450	0.279	1.000	0.396	−0.454	0.101
	0.264	0.684	0.396	1.000	−0.246	−0.215
	0.035	−0.085	−0.454	−0.246	1.000	0.140
	0.107	0.060	0.101	−0.215	0.140	1.000
PCs retained	PC1	PC2	PC3			
Eigenvalues	3.7028	1.0636	0.6961			
Eigenvectors	−0.169	0.585	−0.464			
	−0.246	−0.112	0.428			
	−0.246	−0.116	0.114			
	−0.244	−0.204	0.453			
	−0.121	−0.621	−0.859			
	−0.215	0.382	−0.284			
Variance absorption (%)	0.617	0.177	0.116			
	0.617	0.794	0.91			

Accumulation of variance



Correlated indicators (loadings)			
Greenhouse gas emission	−0.325	0.603	−0.387
Total energy consumption	−0.473	−0.115	0.357
Total waste weight	−0.474	−0.12	0.095
Water consumption	−0.469	−0.21	0.378
Waste recycle rate	−0.233	−0.64	−0.717
Hazardous waste weight	−0.414	0.394	−0.237

component (PC1) is highly correlated with such environmental indicators as total energy consumption (−0.473), total waste (−0.474), and water consumption (−0.469). The second component (PC2) is highly correlated with greenhouse gas emissions (0.603) and waste recycle rate (−0.64). PC3 is highly correlated with waste recycle rate (−0.717).

These indicators can tell the differences of these selected companies in environmental sustainability, and the composite environmental index can be built up for each company with the three PCs, weighted with their eigenvalues. The constructed index results for each company and the benchmarked ranking are shown in Table 6. Among them, 20 companies/year show positive values in environment performance assessments, which are higher than the mean (which is zero). The other ten companies/year show negative values. From the ranked results, we can tell that company 1 and company 5 have the best environmental performance, while company 9, company 6, and company 10 receive the lowest scores on their environmental performance measurement.

In a similar way, PCA analysis is also conducted on six economic and social indicators, shown in Table 4. The PCA results and ranking on the economic and social performance of these companies are shown in Table 6. Four principal components were retained in the analysis of the economic and social dimensions. According to Table 6, the economic and social index is positive in 13 companies/year, while the other 17 show negative values. The highest ranking are with company 2/year 2007, company 11/year 2008, and company 11/year 2007, and the worst performances are all with company 5/years 2005, 2009, and 2008.

PCA analysis results on the composite sustainability indicators are shown in Table 5; 11 indicators are selected as the final set for computing the overall sustainability index, since we discard the indicator (female percentage in

Table 4 PCA results of economic and social indicators

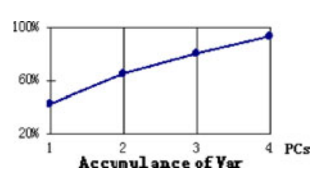
Economic and social						
Correlation matrix	1.000	−0.262	−0.320	−0.081	−0.004	0.285
	−0.262	1.000	0.029	0.380	−0.297	−0.503
	−0.320	0.029	1.000	−0.072	0.093	0.186
	−0.081	0.380	−0.072	1.000	0.252	0.122
	−0.004	−0.297	0.093	0.252	1.000	0.306
	0.285	−0.503	0.186	0.122	0.306	1.000
PCs retained	PC1	PC2	PC3	PC4		
Eigenvalues	2.5774	1.3518	0.9062	0.7775		
Eigenvectors	−0.281	−0.388	0.075	0.181		
	0.361	0.022	0.182	−0.033		
	0.014	−0.596	0.588	−0.135		
	0.332	0.028	0.379	0.447		
	−0.138	0.384	0.639	−0.650		
	−0.222	0.292	0.408	0.781		
Variance absorption (%)	0.43	0.235	0.151	0.129		
	0.43	0.655	0.806	0.935		
Accumulation of variance						
Correlated indicators (loadings)						
Net revenue	−0.451	−0.451	0.071	0.160		
R&D expenditure	0.580	0.026	0.173	−0.029		
Work-related injury freq.	0.022	−0.693	0.560	−0.119		
Charitable contributions	0.533	0.032	0.361	0.394		
Female percentage	−0.222	0.447	0.608	−0.573		
Female percentage in management levels	−0.356	0.340	0.388	0.689		

Table 5 PCA results of composite sustainability indicators

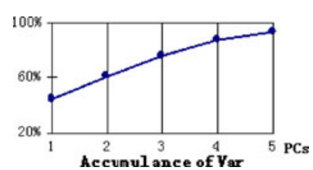
Sustainability indicators											
Correlation matrix											
1.000	−0.262	−0.155	−0.047	−0.142	−0.362	0.146	−0.230	−0.320	−0.079	−0.004	0.285
−0.262	1.000	0.357	0.202	0.099	0.513	0.156	0.404	0.029	0.374	−0.297	−0.503
−0.155	0.357	1.000	0.399	0.450	0.264	0.035	0.107	0.668	0.269	−0.098	−0.041
−0.047	0.202	0.399	1.000	0.279	0.684	−0.085	0.060	0.153	0.863	0.194	0.157
−0.142	0.099	0.450	0.279	1.000	0.396	−0.454	0.101	0.469	0.138	−0.440	−0.171
−0.362	0.513	0.264	0.684	0.396	1.000	−0.246	0.215	−0.025	0.842	−0.065	0.225
0.146	0.156	0.035	−0.085	−0.454	−0.246	1.000	0.140	0.174	0.063.	0.425	0.343
−0.230	0.404	0.107	0.060	0.101	0.215	0.140	1.000	−0.041	0.185	−0.024	−0.361
−0.320	0.029	0.668	0.153	0.469	−0.025	0.174	−0.041	1.000	−0.072	0.093	0.186
−0.079	0.374	0.269	0.863	0.138	0.842	0.063	0.185	−0.072	1.000	0.199	0.116
−0.004	−0.297	−0.098	0.194	−0.440	−0.065	0.425	−0.024	0.093	0.199	1.000	0.306
0.285	−0.503	−0.041	0.157	−0.171	0.225	0.343	−0.361	0.186	0.116	0.306	1.000
PCs retained					PC1	PC2	PC3	PC4	PC5		
Eigenvalues					4.8481	1.8183	1.6807	1.2815	0.6252		
Eigenvectors					−0.128	0.314	0.025	−0.208	0.459		
					−0.167	−0.052	−0.336	−0.002	0.014		
					−0.186	−0.122	−0.055	−0.071	0.183		
					−0.171	−0.133	−0.276	−0.004	0.024		
					−0.068	−0.257	−0.010	−0.587	−0.415		
					−0.172	0.181	0.066	−0.100	0.152		
					−0.136	0.102	0.165	0.126	−1.008		
					0.170	0.096	−0.193	−0.249	−0.238		
					−0.035	0.500	0.086	−0.180	−0.152		
					0.124	0.122	−0.338	−0.355	−0.042		
					0.001	−0.182	0.460	−0.375	0.249		
Variance absorption (%)					0.441	0.165	0.153	0.116	0.057		
					0.441	0.606	0.759	0.875	0.932		
Accumulation of variance											

Table 5 (continued)

Sustainability indicators					
Correlated indicators (loadings)					
Net revenue	−0.281	0.423	0.033	−0.236	0.363
R&D expenditure	−0.368	−0.07	−0.436	−0.002	0.011
Greenhouse gas emission	−0.41	−0.164	−0.071	−0.08	0.145
Total energy consumption	−0.376	−0.18	−0.358	−0.004	0.019
Total waste weight	−0.149	−0.347	−0.013	−0.664	−0.328
Water consumption	−0.378	0.244	0.086	−0.113	0.12
Waste recycle rate	−0.299	0.137	0.214	0.143	−0.797
Hazardous waste weight	0.375	0.13	−0.25	−0.282	−0.188
Work-related injury freq.	−0.078	0.674	0.111	−0.204	−0.12
Charitable contributions	0.272	0.165	−0.438	−0.402	−0.033
Female percentage	0.003	−0.245	0.597	−0.425	0.197

management levels) that gave redundant information. So, in this analysis, $p+q-1=r$. Five principal components are retained, and they explain 93.2% of the total variance of the original data. The PCA analysis results on overall sustainability performance and the benchmarked ranking results are shown in Table 6 in the column PCA_{Stn}. These indicators can suitably explain the differences in overall sustainability among companies. According to Table 6, 19 companies/years show positive values in the composite sustainability index, while the other 11 receive negative values in the relative ranking of sustainability. Among the 30 companies/years, the best sustainability performances are obtained by company 5/year 2008, company 5/year 2009, and company 1/year 2008, while the worst sustainability performances are with company 2/year 2007, company 6/year 2008, and company 9/year 2008.

Through this analysis, the sustainability of the companies can be quantitatively assessed by using the PCA-based composite sustainability indicators. The strengths and weaknesses of each company in their sustainability can be identified, and the improvement opportunities can be obtained by studying each individual indicator. For example, in Table 6, company 9/year 2008 ranks to the final, which is largely because its environmental index is the worst. As we discussed in Table 3, the first component (PC1) is highly correlated with total energy consumption, total waste, and water consumption, so company 9/year 2008 has sustainability problems in these three aspects, and it should take some measures to improve them.

5 Conclusions

This paper introduces a method of evaluating and benchmarking corporate sustainability performance of manufacturing companies based on PCA. To develop this method, industry and academia surveys are conducted to obtain firsthand information on what sustainability indicators are being currently used and favored in a sustainable manufacturing community. In the survey, a total of 32 preferable sustainability indicators are used for collecting the feedback information from both academia and industry, covering the environmental, economic, and social dimensions of the sustainability metric. From the surveys' results, we learned that industry and academia have different views on the same indicators. The multivariate analysis of PCA is used as an objective approach to select the most important indicators relative to corporate sustainability. Then, a composite sustainability index is constructed based on the most important indicators selected. Advantages of this composite sustainability index include a comprehensive analysis of the sustainability performance of manufacturing companies, benchmark and ranking of the company's sustainability performance, as well as identification of improvement opportunities for sustainability management. To illustrate the application of

Table 6 PCA results of studied companies

Company	PCA_{Env}	Ranking	$PCA_{E\&S}$	Ranking	PCA_{Stn}	Ranking
Company 5/year 2008	0.928	4	−1.25	30	0.969	1
Company 5/year 2009	0.879	5	−1.181	29	0.917	2
Company 1/year 2008	1.01	2	−0.731	25	0.84	3
Company 1/year 2009	1.015	1	−0.708	24	0.833	4
Company 1/year 2007	0.996	3	−0.678	22	0.829	5
Company 5/year 2005	0.855	6	−0.976	28	0.812	6
Company 4/year 2007	0.783	8	−0.134	16	0.656	7
Company 7/year 2006	0.806	7	−0.476	20	0.612	8
Company 4/year 2009	0.758	10	−0.186	18	0.611	9
Company 4/year 2008	0.764	9	−0.209	19	0.6	10
Company 7/year 2008	0.627	12	−0.681	23	0.53	11
Company 3/year 2008	0.682	11	−0.084	15	0.508	12
Company 7/year 2007	0.609	13	−0.488	21	0.498	13
Company 3/year 2007	0.37	16	−0.14	17	0.335	14
Company 3/year 2006	0.281	19	−0.076	14	0.262	15
Company 11/year 2006	0.587	14	0.259	13	0.2	16
Company 8/year 2008	0.37	15	0.268	12	0.154	17
Company 2/year 2008	0.343	17	0.347	10	0.137	18
Company 8/year 2007	0.288	18	0.441	9	0.068	19
Company 6/year 2007	−0.34	24	−0.872	27	−0.027	20
Company 8/year 2006	0.064	20	0.515	6	−0.105	21
Company 6/year 2006	−0.41	25	−0.732	26	−0.133	22
Company 8/year 2009	−0.089	22	0.466	7	−0.172	23
Company 10/year 2008	−1.313	27	0.459	8	−0.338	24
Company 10/year 2009	−0.832	26	0.622	5	−0.449	25
Company 11/year 2007	−0.075	21	1.369	3	−0.526	26
Company 11/year 2008	−0.096	23	1.425	2	−0.559	27
Company 2/year 2007	−1.495	28	2.227	1	−1.403	28
Company 6/year 2008	−3.755	29	0.938	4	−2.934	29
Company 9/year 2008	−4.612	30	0.269	11	−3.725	30

this method, a case study is conducted on 11 electronics manufacturing companies.

As conventional LCA practices are expanding to the economical and social dimensions, the composite index constructed in this paper provides a way of solution to address the challenges in the trend. The method evaluates the overall sustainability of the company from three aspects—environmental, economic, and social. The evaluation results in the case study indicate that the environmental aspect alone could not explain the sustainability of the company accurately. Though the impacts of economic and social factors are small, they may play important roles in the overall sustainability measurement. It is necessary to analyze three-dimensional sustainability of the company simultaneously during the conduct of a product LCA. The evaluation results of the traditional LCA are quantitative global warming potential, acidification potential, ozone depletion potential, etc. The method presented in this paper provides a reference for how to choose and quantify economic and social indicators and distribute their weights in the process of conducting economic and social LCA. In addition, during the survey processes, we have noticed that different types of companies have their own preferable characteristics. When sustainability research needs to proceed on different types of companies, favorable indicators and suitable weight factors can be selected based on the characteristics of each company. This goes back to the eigenvalues and PCs, which are affected by each and every type of samples.

Acknowledgments The authors would like to thank the research institutions, universities, and the companies for their participation and support in our survey. The project is funded by the National Basic Research Program of China (grant no. 2011CB013406).

References

Aras G, Crowther D (2007) Sustainable corporate social responsibility and the value chain. In: Crowther D, Zain MM (eds) New perspectives on corporate social responsibility. MARA University Press, Kuala Lumpur, pp 109–128

Dahlsrud A (2008) How corporate social responsibility is defined: an analysis of 37 definitions. Corp Soc Responsib 15(1):1–13

Erhard M, Van Minnen J, Voigt T (2002) Proposed core set of climate change state and impact indicators in Europe, technical report no. XX. EEA, ETC on air and climate change, European Environment Agency, Copenhagen

Hauschild M, Dreyer LC, Joergensen A (2008) Assessing social impacts in a life cycle perspective—lessons learned. CRIP Ann-Manuf Techn 57:21–24

Hossein MH, Shinji K (2011) Dynamic sustainability assessment of countries at the macro level: a principal component analysis. Ecol Indic 11(3):811–823

Jha R, Murthy K (2003) An inverse global environmental Kuznets curve. J Comp Econ 31(2):352–368

Jollands N, Lermit J, Patterson M (2004) Aggregate eco-efficiency indices for New Zealand—a principal components analysis. J Environ Manage 73(4):293–305

Jolliffe IT (2003) Principal component analysis. Springer, New York

Krajnc D, Glavic P (2003) Indicators of sustainable production. Clean Technol Environ 5(3):279–288

Laurent A, Olsen SI, Hauschild MZ (2010) Carbon footprint as environmental performance indicator for the manufacturing industry. CRIP Ann-Manuf Techn 59:37–40

OECD (Organisation for Economic Co-operation and Development) (2002) Indicators to measure decoupling of environmental pressure from economic growth, The OECD Environment Programme. OECD, Paris

Parris TM, Kates W (2003) Characterizing and measuring sustainable development. Annu Rev Environ Resour 28:559–586

Pearson K (1901) On lines and planes of closest fit to systems of points in space. Philos Mag 2:559–572

Quarrie J (1992) The United Nations Conference on Environment and Development-Earth Summit 1992. Rio de Janeiro, Brazil

SAIC (Scientific Applications International Corporation) (2006) Life cycle assessment: principles and practice. EPA, Washington

Saltelli A (2007) Composite indicators between analysis and advocacy. Soc Indic Res 81(1):65–77

Shaw PJA (2003) Multivariate statistics for the Environmental Sciences. Hodder-Arnold, London

Soler RJ, Soler RP (2008) Assessment of aggregated indicators of sustainability using PCA: the case of apple trade in Spain. Proceedings of the 6th Int. Conf. on LCA in the Agri-Food Sector, Zurich, November 12–14, pp 133–414

Veleva V, Ellenbecker M (2001) Indicators of sustainable production: framework and methodology. J Clean Prod 9(6):519–549

Veleva V, Hart M, Greiner T, Crumbley C (2001) Indicators of sustainable production. J Clean Prod 9(5):447–452

WCED (W. C. o. E. a. D.) (1987) Our common future. Oxford University Press, Oxford

Wei J, Zhao YT, Xu HQ, Yu H (2007) A framework for selecting indicators to assess the sustainable development of the natural heritage site. J Mater Sci-Eng 4(4):321–330